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Postharvest Potential of Cold-hardy Table Grapes

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Abstract. **The University of Minnesota Grape Breeding Program has developed cold-hardy wine grape cultivars that have facilitated the establishment of an economically important grape industry for the Midwest region. In recent years, the program has renewed efforts to breed cold-hardy table grapes. Table grapes might require postharvest storage if they are to be transported or stored for any period of time. Rachis dehydration, berry splitting, and decay can affect the postharvest quality of table grapes. In this study, we evaluated these postharvest traits in six released cultivars and nine advanced selections in the breeding program. For two growing seasons, we used industry standard packaging to assess postharvest traits (rachis dehydration, berry splitting, decay, and overall acceptability) at 2, 4, and 6 weeks of cold storage at 2.2 °C. The growing season had a significant effect on postharvest traits; therefore, the two were examined separately. There were significant differences in postharvest storage times for all traits, except berry splitting in 2020. Mean rachis dehydration reached unacceptable values (>3) after 4 weeks of postharvest storage in 2019 and after 6 weeks in 2020. All other trait means remained acceptable for many cultivars even after 6 weeks of postharvest storage. Advanced selections performed at and above the level of released cultivars, suggesting that selections will perform well in cold-hardy regions. The data collected regarding fruit quality and postharvest storage for two seasons will help to inform and improve breeding of cold-hardy grape cultivars.**

The University of Minnesota (UMN) Grape Breeding Program developed cold-hardy wine grape cultivars (*Vitis vinifera*, *V. labrusca*, and *V. riparia*) that have facilitated the establishment of a viable grape industry in the midwest region of the United States (Clark et al., 2019). The development of grape cultivars has been a goal at the UMN for 110 years; since the 1980s, the primary focus has been on wine grape cultivars. In response to grower interest in producing sustainable, locally produced foods for direct-to-consumer markets, the breeding program has recently begun to evaluate and breed cold-hardy table grapes. Expanding into table grapes also provides monetary incentives for local growers, with table grapes selling for $3.00/lb compared with $0.82/lb for wine grapes (Clark et al., 2019). With the developing market for direct-to-consumer sales, and with nearly half of the growers in the Midwest intending to increase the amount of acreage devoted to grapes (Tuck and Gartner, 2013), cold-hardy table grapes are a potential additional fruit crop for local growers.

Table grapes will likely need to be stored before being sold to consumers, even when sold in local markets. Postharvest traits of cold-hardy grape varieties and breeding selections have not been evaluated in Minnesota or, more broadly, in the upper midwest region of the United States. Maintaining fruit quality in storage is important to deliver high-quality fruit to consumers, and low temperature storage at 0 °C is one of the most widely used methods to maintain these quality standards and increase the shelf life (Rosales et al., 2016). However, there are often difficulties with chilling injury, firmness loss, berry drop (also known as shelling or shatter), discoloration of the rachis, and fungal rot (Meng et al., 2008; Rosales et al., 2016). The use of sulfur dioxide (SO_2) is a common method for mitigating fungal decay of tables grapes in storage (Ahmed et al., 2018; Jia et al., 2020). The SO_2 is commonly applied using pads that slowly release gaseous SO_2 into the packaging (Ahmed et al., 2018; Jia et al., 2020). The use of SO_2 pads in storage may be more accessible to small growers who may have access to cold storage but not CA systems that would be required for other treatments typical of traditional table grape production regions (e.g., California or Chile).

In this study, we evaluated UMN advanced breeding selections along with available cold-hardy cultivars for harvest traits and postharvest potential in storage. Grape clusters were harvested and placed into cold storage in carton boxes with SO_2 pads for postharvest storage and destructively evaluated after 2, 4, and 6 weeks of storage. We hypothesized that advanced breeding selections would have fruit quality and postharvest performance similar to those of released cold-hardy cultivars grown in the same environment. Knowledge of how different lines perform in Minnesota and in postharvest conditions will inform growers about best practices and suitable varieties for production. Results will enable more informed parent selection for cold-hardy table grape breeding programs.

Materials and Methods

Plant material. Clusters from 15 own-rooted grapevine cultivars and UMN advanced selections with ≈10 to 15 years of growth were assessed for two seasons (2019 and 2020) to evaluate general cluster traits, fruit chemical composition, and postharvest traits. Named cultivars and UMN advanced breeding selections (indicated as MN####) are collectively referred to as cultivars in this article (Table 1). The grapes were grown at the UMN Horticultural Research Center (HRC), Excelsior, MN (44°52′08.1″N 93°38′17.3″W). Vines were spaced 0.8 m within rows and 3.0 m between rows. The cold-hardy cultivars were trained on a top wire, high-cordon system, whereas the cold-sensitive materials were trained to the mini-J system for winter protection (Hoover and Hemstad, 1993). Of the cultivars evaluated, three were seeded (‘Louise Swenson’, ‘Swenson Red’, and MN1423); the others exhibited stenospermocarpic seedlessness, with six having a seed trace (‘Mars’, MN1213, MN1296, MN1325, MN1376, and MN1387) and six being functionally seedless (‘Jupiter’, ‘Petite Jewel’, ‘Somerset Seedless’, MN1375, MN1380, and MN1424) (Table 1). Growing degree days were calculated using weather data from the HRC from 1 Apr. and a base temperature of 10 °C.

Collection and postharvest. Twelve clusters per cultivar were harvested at maturity when the majority of clusters for the cultivar reached a total soluble solids (TSS) content of at least 14 °Brix. At the time of harvest, three clusters were destructively sampled for fruit quality traits (cluster weight, cluster length, overall rating of acceptability, percent damage, berry size, berry weight, and seed weight) and juice chemical composition (TSS, total titratable acidity, pH, and malic acid concentration). The remaining nine clusters were cleaned of split or decayed berries, randomly sorted into three treatment groups, placed into commercial packaging (clear plastic, vented polyethylene bags), weighed, and placed into storage. For postharvest storage, the filled bags were arranged in cardboard boxes (40.6 × 31.7 × 31.7 cm) lined with a standard microperforated poly liner (1%), absorbent paper pads, and slow release SO_2-generating pads (Osku Hellas, Grapegaurd, Santiago, Chile) containing 73.5% of the active ingredient (a.i.), $Na2S_2O_5$. The absorbent paper pads were placed under the bunches and SO_2 pads were on top of the bunches in each box following commercial standards. Clusters were stored in boxes at 2.2 °C for 2, 4, and 6 weeks. At each

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Table 1. Parentage, color, seed, and growing degree days until harvest for cold-hardy, hybrid grape cultivars and advanced breeding selections grown in Minnesota.

					Harvest		GDD	
	Female parent	Male parent	Color	Seed	2019	2020	2019	2020
Cultivars								
Jupiter	A-1258	A-1672	Black	Seedless	18 Sept.	9 Sept.	2440.7	2612.0
Louise Swenson	E.S. 2-12-13	Kay Gray	Green	Seeded	19 Sept.	9 Sept.	2465.7	2612.0
Mars	Island Belle	A-1339	Reddish-blue	Trace	19 Sept.	9 Sept.	2465.7	2650.7
Petite Jewel	MN78	Canadice	Pink	Seedless	10 Sept.	24 Aug.	2304.0	2345.5
Somerset Seedless	ES 5-3-64	Petite Jewel	Orange/pink	Seedless	10 Sept.	9 Sept.	2304.0	2612.0
Swenson Red	MN78	Seibel 11803	Red	Seeded	17 Sept.	9 Sept.	2417.7	2612.0
Advanced Selections								
MN1213	E.S. 2-12-13	MN1135	Red	Trace	17 Sept.	9 Sept.	2440.7	2612.0
MN1296	Louise Swenson	MN1213	Red	Trace	18 Sept.	9 Sept.	2440.7	2612.0
MN1325	MN1130	MN1213	Reddish-blue	Trace	18 Sept.	9 Sept.	2417.7	2522.3
MN1375	MN1277	MN1213	Green	Seedless	17 Sept.	1 Sept.	2417.7	2522.3
MN1376	MN1277	MN1213	Green	Trace	17 Sept.	1 Sept.	2417.7	2522.3
MN1380	Petite Jewel	Louise Swenson	Green	Seedless	17 Sept.	1 Sept.	2417.7	2190.8
MN1387	Petite Jewel	Louise Swenson	Reddish-blue	Trace	17 Sept.	18 Aug.	2440.7	2650.7
MN1423	MN1130	MN1213	Green	Seeded	18 Sept.	11 Sept.	2465.7	2554.9
MN1424	St. Pepin	MN1296	Green	Seedless	19 Sept.	3 Sept.	2440.7	2612.0

time point, one bag per cultivar containing three clusters was destructively sampled and evaluated for fresh weight, overall rating of acceptability, berry splitting, percent decay, stem dehydration, and weight change in storage. Berries were saved for each genotype, seeds were removed, and dried.

The overall rating of appearance, a proxy for consumer acceptability, was scored using a 5-point scale with the following descriptors: 1, absence of decay or splitting on the cluster; 2, light, only a few berries with decay damage; 3, moderate, a few berries with decay and splitting damage; 4, severe, many berries with decay and splitting damage; and 5, extreme, all berries damaged. The overall rating of appearance is referred to as the overall appearance in the remainder of this article. Stem dehydration was assessed using a scale developed by Lichter et al. (2011), with rachis values ranging from 1 to 5 (1, a completely green rachis; 5, a completely brown rachis). When assessed at harvest, berry damage included splitting and decay and was calculated as a percent by dividing the weight of the total damaged berries by the weight of the cluster and multiplying by 100. For postharvest treatments, the damaged fruit was separated into berries with general decay or split berries, and the percent was calculated as previously described. Berry size was obtained using a caliper to measure the width at the equator of 10 berries per cluster and averaged for each of the three clusters. The weight of each bag containing three clusters was measured before storage, and then again before destructive sampling at the final postharvest week of either 2, 4, or 6 weeks. Shattering was measured by obtaining the weight of the free berries at the bottom of the bag at the time of sampling and dividing by the mass of the three clusters in the bag. The percent weight loss in storage was calculated by taking the difference in the weight of the clusters in a bag before and after storage and dividing by the total weight before storage. All traits were evaluated against the industry standard score of three for overall appearance and rachis dehydration and 3% for decay and splitting (unpublished). Consumer acceptability was considered based on the industry standard. The U.S. Department of Agriculture (USDA) standards for American (Eastern Type) bunch grapes are more stringent for decay and allow 10% total damage, including, but not limited to, decay, splitting, and shatter (USDA, 2016).

Juice chemical composition data were collected at each time point, including harvest and 2, 4, and 6 weeks after harvest. The TSS was collected by taking the juice of five selected berries from the base, middle, and top of each cluster and measuring it with a Misco® PA 201 digital refractometer (Solon, OH). To obtain a sufficient juice volume to measure the total titratable acid (TA) (g/L), representative berries remaining after sampling were pooled together, and the one juice was measured in triplicate using the Metrohm® 916 Ti Touch auto titrator (Herisau, Switzerland) and Fischer Scientific® Acumet AR15 pH meter (Fair Lawn, NJ). The TA was determined using 0.1 mol/L NaOH solution to titrate each juice sample diluted in 1:4 deionized water, with tartaric acid used as a standard. A subset of the juice was aliquoted and stored to measure malic acid using the L-Malic Acid Assay Kit (Megazyme Ltd.) in triplicate. The maturity index was calculated by dividing the TSS by the percent of TA.

Statistical analyses. Analyses of variances (ANOVAs) were performed to determine if average trait values (i.e., cluster length and weight, berry size and weight, percent splitting, and percent decay) varied significantly among treatments. Mean separation was performed using the Tukey-Kramer honestly significant difference test. Comparisons of ranked variables (i.e., overall appearance and rachis dehydration) were performed using the Kruskal-Wallis one-way ANOVA. Dunn's test with a Holm–Bonferroni correction was used for mean separation. All statistical analyses were performed using R (R Core Team, 2016) with the *FSA* (Ogle et al., 2021), *agricolae* (de Mendiburu and Yaseen, 2020), and *diplyr* (Wickham et al., 2021) packages.

Results

A total of 15 individuals (six named cultivars and nine advanced selections) were assessed for two growing seasons (2019 and 2020). Variations were observed among the individuals tested for growing degree days at the harvest date and ranged from 2304.0 to 2465.7 in 2019 and 2190.8 to 2650.7 in 2020 (Supplemental Table S1; Supplemental Fig. S1). The average dry seed weight varied from 8.7 mg (seedless) to 378.9 mg (fully seeded) (Table 1). 'Jupiter' had berries that were elliptical in shape, and all other cultivars had round berries.

Cluster lengths and weights at harvest varied by cultivar, with cluster weight also varying significantly ($P < 0.01$) by season (Table 2). Average cluster lengths ranged from 12.0 cm ('Somerset Seedless') to 19.1 cm (MN1376). Average cluster weights ranged from 36.7 g to 227.3 g in 2019, and from 67.7 g to 324.5 g in 2020 (Table 2). MN1213 had the largest clusters, one of the highest average weights, and longest clusters. MN1424 had lowest average cluster weights in 2019, and the average cluster weight was low in 2020; however, it was not significantly different from that of other cultivars. 'Louise Swenson', 'Petite Jewel', 'Somerset Seedless', MN1296, MN1325, MN1375, MN1380, MN1387, and MN1423 also had small average cluster weights in 2020. 'Somerset Seedless' and MN1243 had the shortest clusters. Similarly, the overall ranges of berry weights and sizes varied by cultivar (Table 2). Berry sizes also varied significantly ($P < 0.01$) by season, with berries in 2020 being larger, on average, than berries in 2019. 'Swenson Red' had the largest berries, with an average 10-berry weight of 38.6 g and average berry diameter of 18.8 mm in 2019 (Table 2). 'Petite Jewel' had the smallest berry diameter (10.7 mm) in 2019, and MN1387 had the smallest berry diameter (11.1 mm) in 2020. MN1387 also had the smallest 10-berry weight (8.6 g) (Table 2).

Table 2. Harvest data for cold-hardy grape cultivars and advanced breeding selections grown in Minnesota with post hoc groups determined by Tukey's honestly significant difference test within each treatment year. Cluster weight and berry size were significantly different by year ($P < 0.001$). All traits (except average seed weight) differed significantly ($P < 0.01$) by cultivar. University of Minnesota (UMN) advanced breeding selections are indicated as MN####.

Cultivars	Cluster length (cm) 2019 and 2020	Cluster wt (g)		10 Berry wt (g) 2019 and 2020	Berry size (mm)		Avg seed wt (mg)
		2019	2020		2019	2020	
Jupiter	13.1 bc	64.0 bc	192.2 ab	29.7 b	14.4 c	16.6 ab	8.7
Louise Swenson	13.0 bc	162.7 ab	129.8 b	28.7 b	16.5 b	16.6 ab	230.7
Mars	12.7 bc	104.1bc	180.4 ab	25.2 bc	14.8 c	16.3 ab	5.0
Petite Jewel	14.3 abc	98.7 bc	152.1 b	11.0 fg	10.7 j	12.2 ef	43.0
Somerset Seedless	12.0 c	89.4 bc	147.9 b	15.8 ef	12.9 gh	13.1 de	73.0
Swenson Red	16.6 abc	111.2 abc	225.8 ab	38.6 a	18.8 a	17.8 a	378.9
MN1213	19.0 a	227.3 a	325.4 a	29.9 b	16.6 b	16.7 a	93.3
MN1296	14.7 abc	73.2 bc	103.9 b	16.9 de	13.4 fg	13.7 de	51.3
MN1325	15.1 abc	118.0 abc	108.4 b	13.6 efg	12.7 h	13.0 e	71.0
MN1375	17.8 abc	94.2 bc	141.6 b	17.8 de	13.6 efg	14.6 cd	22.5
MN1376	19.1 a	117.4 abc	182.2 ab	15.8 ef	13.7 def	13.4 de	55.3
MN1380	12.7 bc	106.4 abc	127.3 b	21.9 cd	14.2 cde	15.2 bc	70.7
MN1387	18.5 ab	91.2 bc	75.2 b	8.6 g	11.5 i	11.1 f	17.0
MN1423	12.6 c	171.3 ab	96.3 b	18.5 de	14.4 cd	13.6 de	298.0
MN1424	12.9 bc	36.7 c	67.7 b	11.0 fg	11.6 i	12.2 ef	35.0

The advanced selections had harvest values similar to those of the cultivars, and some had larger berry and cluster sizes than cultivars.

The TSS ranged from 14.6 °Brix to 23.7 °Brix in 2019, and it was similar in 2020, although higher, ranging from 16.7 °Brix to 25.4 °Brix (Table 3; Supplemental Table S1). The TSS was not significantly different according to postharvest treatment weeks (Supplemental Table S1). The TA had a lower range in 2020 (3.9–12.3 g/L) than in 2019 (5.5–14.1 g/L). The TA values were relatively similar between years, but with different ranges, However, in 2020, there was large decrease in the TA of 'Jupiter', 'Somerset Seedless', 'Swenson Red', MN1213, and MN1296, which were all collected after a heavy rain and hail event (Northeast Weather Association, 2020). These cultivars had the highest maturity index values in 2020. The pH range was similar in 2019 (2.5–3.3) and 2020 (2.9–3.3). The maturity index was higher in 2020 (range, 17.9–52.8) than in 2019 (range, 10.4–37.1). MN1325 and 'Petite Jewel' had the highest TSS and the highest TA of all the cultivars.

During the postharvest evaluation, overall appearance, rachis dehydration, and decay were all significantly different ($P < 0.05$) at each storage week, whereas splitting was not (Table 4). All traits increased (quality decreased) significantly from 2 weeks of storage to 6 weeks. The average at 4 weeks was intermediate or not significantly different from that at 2 weeks and 6 weeks. The overall appearance and rachis dehydration had lower values after 6 weeks of postharvest storage in 2020. Percent decay was significantly lower at 2 weeks than at 4 weeks and 6 weeks in 2019. However, in 2020, decay was significantly higher at 4 weeks than at 6 weeks; at 2 weeks, decay was intermediate. In addition to the postharvest treatment, all traits also varied significantly ($P < 0.01$) among cultivars (Table 4). Overall appearance in 2019 did not have enough variation by cultivar to performing grouping after post hoc tests. Additionally, the percent decay and percent splitting (2019) had significant ($P < 0.01$) cultivar × treatment interactions.

The response to postharvest storage varied by season and cultivar. In 2019, most cultivars remained at or below the consumer threshold (three) for overall appearance at all 6 weeks of storage, where 'Petite Jewel', 'Somerset Seedless', and 'Swenson Red' exceeded the threshold at 6 weeks (Table 5). For rachis dehydration in 2019, five of the cultivars were at or below the consumer threshold (three) at 4 weeks of storage, whereas 'Mars', MN1387, and MN1423 exceed the threshold at 6 weeks. 'Jupiter', 'Swenson Red', MN1424, and MN1380 exceeded the threshold at 2 weeks of storage. 'Louise Swenson' and MN1376 remained below the threshold at 6 weeks (Table 5). Thirteen of the 15 cultivars remained below the consumer threshold of 3% splitting at 6 weeks (Table 6). In 2019, 'Petite Jewel' exceeded the consumer threshold for splitting at 6 weeks, whereas 'Somerset Seedless' exceeded the threshold at 2 and 4 weeks; however, clusters assessed at 6 weeks had a

Table 3. Juice chemical composition data at harvest for cold-hardy grape cultivars and advanced breeding selections grown in Minnesota. The total soluble solid (TSS) value is an average of three clusters with the juice of five berries per cluster. Titratable acid (TA) and malic acid (MA) are averages of three technical replicates from pooled samples. The pH is a single value from the pooled samples. University of Minnesota (UMN) advanced breeding selections are indicated as MN####.

	TSS (°Brix)		TA (g/L)		MA (g/L)		pH		MI	
Cultivars	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
Jupiter	18.6	20.6	6.7	3.9	2.1	2.5	2.9	3.2	27.8	52.8
Louise Swenson	15.8	16.7	5.5	4.8	3.0	2.5	2.9	3.1	28.7	34.8
Mars	16.7	16.7	6.5	4.2	2.1	1.1	3.0	3.0	25.7	39.8
Petite Jewel	21.9	20.0	11.1	11.2	7.0		3.1	3.1	19.7	17.9
Somerset Seedless	19.2	20.3	10.1	5.3		4.0	3.3	3.3	19.0	38.3
Swenson Red	18.3	21.2	7.8	5.8	4.3	2.9	2.9	3.1	23.5	36.6
MN1213	20.2	20.2	7.0	4.5	3.0	2.0	3.0	3.2	28.9	44.9
MN1296	20.8	21.9	5.6	4.4	2.3	2.0	3.1	3.2	37.1	49.8
MN1325	23.7	25.4	12.6	12.3	6.5	3.9	2.7	2.9	18.8	20.7
MN1375	18.9	20.9	9.6	9.0	3.1	2.5	2.7	2.9	19.7	23.2
MN1376	18.2	18.0	6.6	5.9	2.0	1.6	2.9	2.9	27.6	30.5
MN1380	21.0	20.9	5.9	5.9	3.1	3.0	3.0	3.2	35.6	35.4
MN1387	20.7	21.0	8.1	9.7	4.4	4.9	2.8	2.9	25. 6	21.7
MN1423	14.6	23.2	14.1	9.2	8.4	4.3	2.5	2.9	10.4	25.2
MN1424	17.7	20.5		5.9		1.4		2.9		34.8

Juice chemical composition data are missing for some values.

Table 4. Fruit quality data for cold-hardy grape cultivars and advanced breeding selections grown in Minnesota after postharvest cold storage (2.2 °C). Appearance is an estimate of consumer acceptability ranging from 1 (no damage) to 5 (all berries damaged), and rachis dehydration is scored from 1 (all green rachis) to 5 (all brown rachis). Cultivar values are an average of all postharvest measurements.

	Appearance (1–5)[i]		Rachis (1–5)[i]		Splitting (%)		Decay (%)	
	2019	2020	2019	2020	2019	2020	2019	2020
ANOVA								
Treatment	**	*	***	***	ns	ns	***	***
Cultivar	**	***	***	***	***	***	***	**
T × C	—	—	—	—	***	**	***	ns
Postharvest Treatment								
2 weeks	2.2 a	1.6 a	2.7 a	1.8 a	ns	ns	0.8 b	0.8 ab
4 weeks	2.4 ab	1.8 a	3.2 b	2.5 b	ns	ns	2.0 a	0.6 b
6 weeks	2.7 b	2.1 b	3.8 c	3.2 c	ns	ns	2.6 a	1.5 a
Cultivar values								
Jupiter	2.7	2.2 abc	4.0 ab	2.8 ab	0.0 b	1.5 c	0.1 b	2.3 abc
Louise Swenson	2.1	1.6 abc	2.3 bc	3.2 ab	1.8 b	2.5 bc	0.2 b	0.7 bcd
Mars	2.4	1.6 ab	2.8 bc	2.2 ab	0.5 b	2.5 bc	1.2 b	0.2 bcd
Petite Jewel[ii]	2.9	1.5 abc	2.8 bc	2.2 abc	2.8 b	0.5 c	2.5 ab	0.4 bcd
Somerset Seedless	3.0	2.1 abc	3.8 abc	1.6 b	7.5 a	2.5 bc	4.8 a	2.5 ab
Swenson Red	2.9	1.4 ab	3.6 abc	2.1 ab	0.1 b	2.8 bc	2.7 ab	0.3 bcd
MN1213	2.3	1.9 abc	3.1 abc	1.9 ab	1.3 b	3.0 bc	2.8 ab	0.3 bcd
MN1296	2.3	2.0 abc	3.4 abc	3.1 ab	0.2 b	6.0 ab	1.2 b	0.4 bcd
MN1325	2.4	1.9 abc	3.4 abc	2.8 ab	0.0 b	0.3 c	1.8 ab	1.4 abcd
MN1375	2.2	1.2 a	3.4 abc	2.7 ab	0.0 b	0.6 c	1.6 b	0.5 bcd
MN1376	2.2	1.6 abc	2.2 c	2.0 ab	1.7 b	2.5 bc	1.2 b	0.1 cd
MN1380	2.6	2.7 bc	3.9 abc	2.9 ab	0.2 b	9.2 a	1.8 ab	0.6 bcd
MN1387[ii]	2.9	3.3 c	3.1 abc	2.4 ab	0.4 b	0.6 c	3.2 ab	3.4 a
MN1423	2.0	1.4 ab	3.1 abc	1.8 ab	1.3 b	3.1 bc	0.4 b	1.4 abcd
MN1424	2.3	1.1 a	4.8 a	3.3 a	0.0 b	1.1 c	1.7 b	0.0 d

[i] Overall appearance was analyzed using the Kruskal-Wallis test followed by Duncan's test for mean separations, T × C interactions were not calculated for these traits (—).

[ii] MN1387 was based on 2 and 4 weeks of postharvest storage, and Petite Jewel in 2020 was based on week 6 data only.

University of Minnesota (UMN) advanced breeding selections are indicated as MN####.

*Significance codes of the analysis of variance (ANOVA) results: *** = 0.001; ** = 0.01; * = 0.05; ns = no significance. Post hoc groups were determined by Tukey's honestly significant difference test.

lower percent of splitting (Table 6). Regarding the percent decay in 2019, the majority of cultivars remained below the consumer threshold (three) at 6 weeks. MN1387 exceeded the threshold at 2 weeks, and 'Somerset Seedless' and MN1213 exceeded the threshold at 6 weeks. 'Petite Jewel' and 'Swenson Red' exceeded the threshold at 4 weeks, but clusters assessed at 6 weeks were below the threshold (Table 6).

Fewer cultivars in 2020 than in 2019 exceeded the consumer threshold for overall appearance in storage. 'Jupiter' exceeded the threshold at 6 weeks. MN1387 exceeded consumer threshold at 4 weeks of storage, whereas clusters assessed at 6 weeks were below the threshold (Table 5). In 2020, rachis dehydration scores for six cultivars remained below or at the consumer threshold (three) at 6 weeks (Table 5). 'Louise Swenson', MN1213, MN1296, and MN1424 exceeded the consumer threshold at 4 weeks. 'Jupiter', 'Mars', MN1325, MN1376, MN1380, and MN1387 exceeded the consumer threshold at 6 weeks of storage (Table 5). Percent splitting had more postharvest week variation in 2020 than in 2019. 'Louise Swenson', 'Mars', 'Swenson Red', MN1213, and MN1296 had inconsistent patterns of consumer threshold being exceeded or met at different treatment weeks (Table 6). Five cultivars (Petite

Table 5. Fruit quality data of cold-hardy grape cultivars and advanced breeding selections grown in Minnesota after postharvest cold storage (2.2 °C). Appearance is an estimate of consumer acceptability ranging from 1 (no damage) to 5 (all berries damaged), and rachis dehydration is scored from 1 (all green rachis) to 5 (all brown rachis). Weekly postharvest values are the average of three clusters destructively sampled at each postharvest treatment. Bold indicates that values are more than the consumer threshold for consumer acceptability (or lower quality). University of Minnesota (UMN) advanced breeding selections are indicated as MN####.

	Appearance (1–5)						Rachis (1–5)					
	2019			2020			2019			2020		
Cultivars	W2	W4	W6	W2	W4	W6	W2	W4	W6	W2	W4	W6
Jupiter	3.0	2.0	3.0	1.7	1.7	**3.3**	**3.7**	**3.3**	**5.0**	2.0	2.3	**4.0**
Louise Swenson	2.0	2.0	2.3	1.7	1.3	1.7	2.0	2.0	2.3	2.0	**4.0**	**3.7**
Mars	2.3	2.0	3.0	1.0	1.3	2.3	2.7	2.3	**3.3**	1.3	2.0	**3.3**
Petite Jewel	2.0	3.0	**3.7**	1.7	—	1.3	1.7	**3.3**	**3.3**	1.0	2.7	3.0
Somerset Seedless	2.3	3.0	**3.7**	1.7	1.7	3.0	2.7	**3.7**	**3.3**	1.0	1.7	2.0
Swenson Red	2.3	3.0	**3.3**	1.3	1.3	1.7	3.0	**3.3**	**4.3**	1.7	2.3	2.3
MN1213	2.0	2.0	3.0	1.3	1.7	2.7	2.0	**3.7**	**3.7**	1.0	1.7	3.0
MN1296	2.0	3.0	2.0	2.0	1.7	2.3	2.3	**3.3**	**4.7**	2.0	**3.3**	**4.0**
MN1325	2.3	2.3	2.7	1.3	2.0	2.3	2.7	**3.7**	**4.0**	2.0	3.0	**3.3**
MN1375	2.3	2.3	2.0	1.3	1.0	1.3	2.7	**3.7**	**4.0**	2.7	2.3	3.0
MN1376	2.0	2.3	2.3	1.3	1.7	1.7	2.3	2.3	2.0	1.0	1.7	**3.3**
MN1380	2.0	3.0	3.0	2.7	2.3	2.0	**3.7**	**4.0**	**4.0**	3.0	2.3	**3.3**
MN1387	2.7	3.0	2.0	2.7	**4.7**	2.7	2.3	2.7	**5.0**	1.0	2.7	**3.7**
MN1423	2.0	2.0	2.0	1.3	1.3	1.7	2.7	3.0	**3.7**	1.0	2.0	2.3
MN1424	2.3	2.0	2.7	1.0	1.3	1.0	**4.7**	**4.7**	**5.0**	2.3	**3.3**	**4.3**

Table 6. Fruit quality data of cold-hardy grape cultivars and advanced breeding selections grown in Minnesota after postharvest cold storage (2.2 °C). Weekly postharvest values are the average of three clusters destructively sampled at each postharvest treatment. Bold indicates values are more than the consumer threshold for consumer acceptability. University of Minnesota (MN) advanced breeding selections are indicated as MN####

	Splitting %						Decay %					
	2019			2020			2019			2020		
Cultivars	W2	W4	W6	W2	W4	W6	W2	W4	W6	W2	W4	W6
Jupiter	0	0	0	0	1.1	**3.4**	0.3	0	0	**3.9**	1.4	0
Louise Swenson	1.7	1.8	1.8	**4.3**	2.1	1.2	0	0.5	0	0	0.8	1.4
Mars	1.6	0	0	2.5	**3.4**	1.5	0.7	0.1	2.9	0	0.3	0.4
Petite Jewel	1.2	1.9	**5.4**	0		1.0	0.8	**4.2**	2.7	0.1		0.7
Somerset Seedless	**14.6**	**8.0**	0	0	3.1	**4.5**	1.5	1.5	**11.5**	2.8	0.5	**4.1**
Swenson Red	0	0	0.4	0	**5.5**	3.0	1.1	**4.1**	3.0	0	0	0.8
MN1213	0	2.2	1.7	**3.1**	2.7	**3.1**	1.0	2.4	**5.0**	0	0	0.9
MN1296	0.5	0	0	**12.1**	**3.6**	2.2	0.4	**4.4**	0	0	0	1.3
MN1325	0	0	0	0	0	0.8	1.3	3.0	0.9	0.9	0.7	2.6
MN1375	0	0	0.1	1.3	0.3	0.2	0.7	1.8	2.3	0	0.4	0.9
MN1376	0.6	1.9	2.5	0	**3.4**	**4.1**	0.5	0.8	2.2	0.1	0.2	0
MN1380	0.5	0		**11.4**	**6.9**	**9.2**	0.7	1.6		0.6	0.2	1.0
MN1387	0.6	0		1.9	0	0	**3.1**	**4.1**		1.8	**3.9**	**3.7**
MN1423	1.9	0.9	1.0	2.9	**3.3**	**3.2**	0.5	0.2	0.6	1.1	0.6	2.7
MN1424	0	0	0	0	2.4	1.0	0.1	3.1	1.8	0	0	0

Jewel, MN1325, MN1375, MN1387, MN1424) remained under the consumer threshold for percent splitting for all treatment weeks (Table 6). MN1380 exceeded the consumer threshold at 2 weeks (Table 6), MN1376 and MN1423 exceeded the consumer threshold at 4 weeks, and ‘Jupiter’ and ‘Somerset Seedless’ exceeded the consumer threshold at 6 weeks (Table 6). In 2020, 12 cultivars remained below the consumer threshold for percent decay (three) at 6 weeks (Table 6). MN1387 exceeded the threshold at 4 weeks, and ‘Somerset Seedless’ exceeded the threshold at 4 weeks. ‘Jupiter’ exceeded the threshold at 2 weeks, but was below the threshold at 4 weeks and 6 weeks (Table 6).

The majority of cultivars remained under the total damage threshold of 10% required by the USDA when including percent damage, splitting, and decay (Fig. 1). However, ‘Somerset Seedless’ was over the standard at 2 weeks of storage in 2019, and it had the highest total damage at 15% (Fig. 1). ‘Swenson Red’ was over the standard at 4 weeks of storage (10.7%), and MN1387 was over the standard at 6 weeks (12.7%) (Fig. 1). In 2020, MN1380 was over the standard at 2 weeks and 6 weeks of storage (12% and 10.4%) (Fig. 1). MN1296 was over the threshold at 2 weeks in 2020 (15.7%), but it was below the threshold at 4 weeks and 6 weeks (Fig. 1).

The percent of shattered berries was lower overall in 2020, with all cultivars having values less than 4% through 6 weeks of storage; however, in 2019, the percent of shatter was as high as 10% (MN1387). Shattered berries

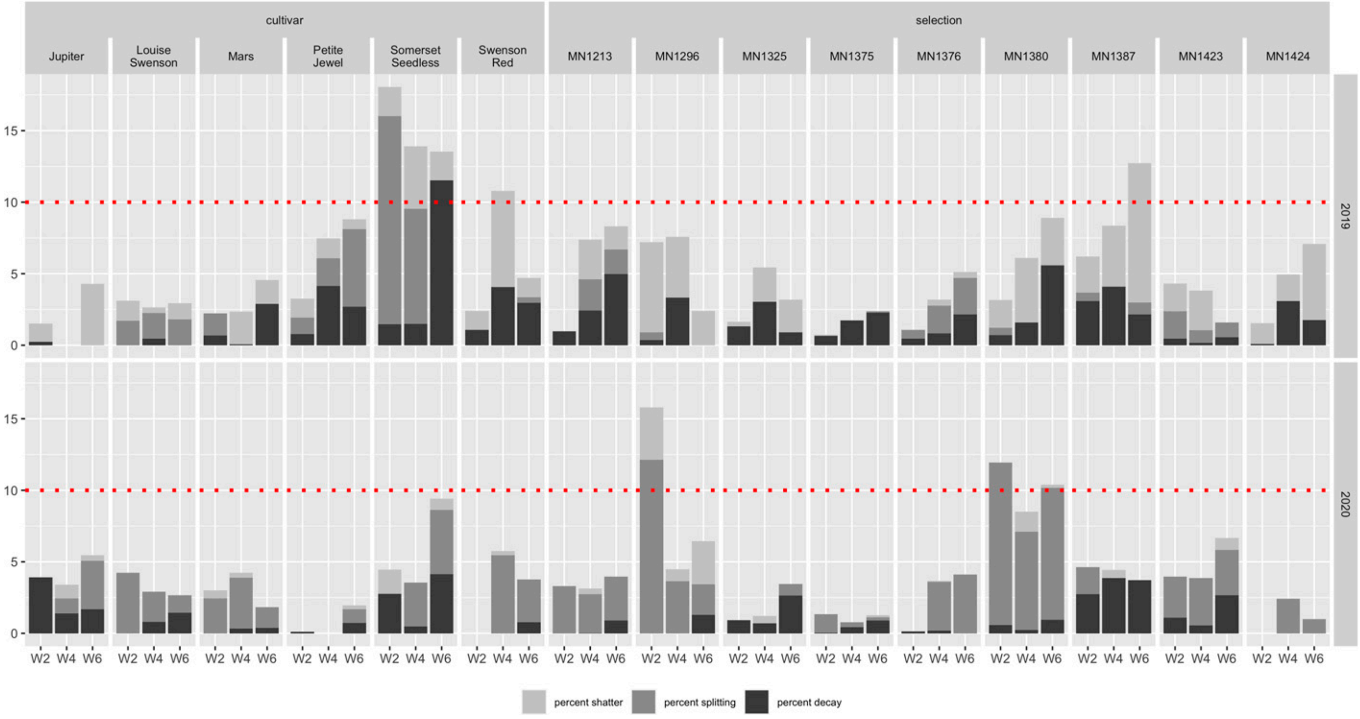

Fig. 1. Stacked bar chart of the total damage, including percent shatter, percent splitting, and percent decay for cold-hardy grape cultivars and advanced breeding selections (MN####) grown in Minnesota in cold storage (2.2 °C) for 2, 4, and 6 weeks. The red dashed line indicates the 10% total damage allowed by U.S. Department of Agriculture (UDSA) guidelines for bunch grapes.

varied (0%–10%) among cultivars, but most had the highest values at 4 weeks of storage and lower values after 6 weeks (Supplemental Fig. S2). Percent weight loss was less than 5% both years (Supplemental Fig. S3). The slope of the linear trend line (1.3) in 2019 was higher than the trend (0.95) in 2020 (Supplemental Fig. S3).

Discussion

Fruit quality and postharvest data were collected for two growing seasons from 15 cultivars. These data are some of the first collected regarding cold-hardy table grapes grown in Minnesota. Of the 15 cultivars examined, the advanced selections from the UMN breeding program performed similarly to named cultivars. Two seasons of data regarding cluster size and berry size of grapes grown in Minnesota allowed for advanced selections to be grouped in size categories that could be used by growers and breeders. Many advanced selections outperformed cultivars with lower splitting and decay values. Results varied between the two years; some cultivars performed better (e.g., less decay or less splitting) in one year compared with the other year. Similarly, decay was generally more prevalent in 2019, whereas splitting was more common in 2020. Fruit quality and postharvest data will allow for more informed parent selection during the breeding process.

Cultivars grown in Minnesota had fruit quality values similar to those of recorded trials performed in other locations, suggesting that advanced selections will do as well, if not better, in other locations growing cold-hardy cultivars. For example, 'Jupiter' had a slightly smaller cluster weight in 2019 (64 g); however, in 2020, it has an average (192.2 g) similar to values of 154 g to 221 g published in the cultivar release paper. Berry size was slightly smaller (3 g vs. 4.3 g) than published size values observed in Arkansas, but the TSS at harvest was similar (20.6 vs. 19.8) (Clark and Moore, 1999). In this study, 'Jupiter' was grown on a mini-J system for winter protection. The low cluster weight in 2019 was potentially caused by hot, windy weather during the bloom period, which resulted in more undeveloped shot berries. Vance et al. (2017) reported similar challenges with 'Jupiter' when grown in Oregon because of precipitation during the bloom period. 'Mars' cluster weight values (104.1 g and 180.4 g) at the HRC were within the range of published values, with smaller berry size (2.5 g vs. 3.9 g) and TSS slightly lower (16.7 vs. 17.6) than those of berries grown in Arkansas (Clark and Moore, 1999). 'Somerset Seedless' had higher cluster weights (89–147.9 g) than those in Montana (25 g) with higher berry weights (1.3 g vs. 0.9 g); however, the berries had lower TSS (20.3 vs. 23.9) (WARC, 2016). The difference in 'Somerset Seedless' grown in Minnesota might have been caused by the tendency for the berries to split with moisture (humidity or precipitation), leading to earlier harvest at a lower TSS and higher TA. For 'Louise Swenson', cluster weights at the HRC (129.9–162.7 g) were above the standard weight expected (70–130 g) for the cultivar with similar berry weights (2.9 g vs. 3 g) (MGGA, 2018). In general, cultivars grown in Minnesota might have higher TA because of the shorter growing season. The fruit quality of cold-hardy cultivars grown in Minnesota is similar to those of cultivars in growing trials in other growing regions, suggesting that new advanced selections from the UMN breeding program will do well when grown where cold-hardy grapes are necessary.

The UMN advanced selections had cluster and berry sizes similar to those of the released cultivars. In general, the selections were grouped into small, medium, and large categories. These could be arbitrary groupings used during the breeding process. For instance, MN1213 would be considered large with heavier clusters, higher berry weight, and larger berries, and they would be comparable to 'Louise Swenson' or 'Swenson Red'. The medium category would contain MN1325, MN1376, and MN1380, which had clusters and berries of intermediate size when compared to the average values for the two years. Medium clusters would be comparable to 'Mars' or 'Jupiter' when grown locally. Finally, the small category would include MN1296, MN1375, MN1387, MN1423, and MN1424, and the smallest clusters and berries, on average, and would be comparable to 'Petite Jewel' or 'Somerset Seedless'. Only MN1296 and MN1424 were smaller than any of the released cultivars; however, they had berries larger than 'Petite Jewel'. Categorizing the advanced selections by size might help with future breeding decisions because smaller-berried cultivars are most prevalent among current seedless progeny populations (personal observation) and less desirable among consumers (Munoz-Espinoza et al., 2020).

Overall, most cultivars remained under the consumer threshold through at least 4 weeks of postharvest storage. When averaging across all cultivars over postharvest treatment, the average overall appearance was significantly different at each storage period, but it never went above the consumer threshold of three in both years, and percent decay had a similar trend. Some cultivars exhibited a year effect for the different traits. For instance, 'Somerset Seedless' had low values for overall appearance and rachis dehydration in 2020 throughout postharvest evaluation, but it exceeded the consumer threshold after 2 weeks of storage in 2019; this is highlighted in the percent splitting and decay, which are components of overall appearance. Overall rachis dehydration remained below the consumer threshold in both years after 2 weeks of storage, but it exceeded the threshold in 2019 after 4 weeks and in 2020 after 6 weeks. Rachis dehydration varied by cultivar, and most cultivars had more rachis dehydration in 2019 than in 2020. This may have occurred because of better growing conditions in 2020, which resulted in better-quality clusters going into storage. For instance, 'Jupiter' had smaller clusters in 2019, with smaller berries, and rachis had more dehydration in 2020. Weight loss followed the expected trend, with more water being lost with each week of storage. Three advanced selections, including MN1325, MN1375, and MN1376, had lower values (i.e., higher quality) for many of the traits than any of the other cultivars.

Percent splitting was not significant by treatment, but it varied by cultivar. In 2019, all cultivars except Somerset Seedless and Petite Jewel remained under the consumer threshold of three for percent splitting throughout the full 6 weeks of storage. Percent splitting in 2020 was highly variable between cultivars and treatments. This variability was more apparent in cultivars that were harvested after a large storm that included hail. Previous work has shown that rain can lead to berry splitting and reduced quality during storage (Strik, 2011; Vance et al., 2017), and it could have been the cause of more splitting in 2020 than in 2019. Percent decay also varied significantly by cultivar during storage treatments/weeks. 'Somerset Seedless' exceeded the consumer threshold in both years after 6 weeks of storage, whereas MN1387 had percent decay at or above the consumer threshold after only 2 weeks of storage. Decay was higher on average in 2019 than in 2020, whereas splitting had a reverse trend, with higher values in 2020.

When looking at the threshold for total damage less than 10% required by the USDA for bunch grapes (USDA, 2016), a few additional advanced selections would be promising. In fact, only MN1387 was above the threshold in 2019, and MN1296 and MN1389 were the only two that were above the threshold in 2020 when total damage was measured. However, the USDA only allows 1% of the total damage to be attributable to mold or decay (USDA, 2016). Although gray mold was rare during postharvest storage of the grapes in this study, the amount of decay in some of the cultivars would exceed this threshold early during storage. However, the USDA standards would not be applicable in the market where cold-hardy table grapes would likely be for sale. The market for cold-hardy grapes is new, especially in Minnesota, and would most likely include small to medium farms, which tend to prefer direct markets such as farmer's markets, consumer-supported agriculture, pick your own, and custom orders (Brady et al., 2010). Farmers markets, consumer-supported agriculture, and other direct markets would allow for individual clusters to be cleaned and damage to be removed compared with large shipments with clusters that are already packaged for sale. In addition, grapes bought at local markets are sold during a shorter time period and are generally set-up for more frequent visits such as weekly pick-up in the case of consumer-supported agriculture. Direct market grapes are also more likely to be consumed quickly when purchased; therefore, there is less need for a longer storage period after sale. The 'Kyoho' grape, which is widely grown and sold in China, was found to last 4.46 d after consumer purchase direct from a wholesaler (Ma et al., 2016). Although it is important to consider total damage as outlined by the USDA, it might not have as strong of an influence when assessing the advanced selections for breeding for direct markets.

One of the main challenges posed during this study was the limited number of clusters available for each cultivar. Many of the cultivars, particularly the advanced selections, are represented by single vines in the breeding program. The limited number of fruit and destructive sampling required resulted in possibly insufficient replication of some individuals. Some of the variation we saw for cultivars at the different storage weeks might be attributable to the limited number of clusters at each postharvest sampling week. Because destructive sampling does not allow the same clusters to be measured from harvest through each storage point, there is also variability between clusters used for each storage treatment with potential bias because they were being separated for storage weeks. Fewer clusters also meant less juice for chemical composition analysis; therefore, there were too few samples for sufficient biological replication for statistical tests other than the initial TSS from berries. In future studies, being able to add more clusters to the study may help with accounting for the variability at each postharvest treatment. More clusters would also allow for additional replication and a more robust sampling of juice for chemical analysis that would give power to the statistical analyses.

The ratios of sugars and acids also enhance the flavor of grapes; in commercial vineyards, table grapes are harvested when the maturity index is ≈20 (Crisosto and Smilanick, 2014; Maoz et al., 2020). Overall, the TSS of the fruit in Minnesota was higher than the 14 to 17.5 °Brix that table grapes would commonly have when picked for harvest in traditional production regions. This is primarily driven by the fact that cold-hardy grapes based in *V. riparia* also tend to have higher TA than fresh-eating cultivars with a *V. vinifera* background. This might be caused by the higher sugar balancing the higher acid, or by producers allowing the fruit to ripen so acid levels have time to decrease while aromatic compounds increase. In addition, unexpected weather events, like rain and hail after veraision, can influence some of the basic chemistry properties, including reducing TA through dilution, as seen in some cultivars in 2020. With cold-hardy table grapes going into local markets where postharvest storage is likely short, the higher maturity index will not be problematic. In fact, it may provide berries that are more appealing to consumers because of further ripening and more developed flavors.

Conclusion

The data collected regarding fruit quality and postharvest storage for two growing seasons will help to inform and improve breeding decisions to further advanced selections in the UMN breeding program. The ability to compare advanced selections with named cultivars will provide a baseline for expectations of quality of cold-hardy table grapes that are available on the market. By adding data from postharvest storage, breeding decisions will be more robust and include data beyond the usual fruit quality, flavor, and growth metrics used. Although the global table grape industry requires long storage periods and shipping long distances, a local table grape industry may not require such rigorous storage standards. Some varieties are harvested before peak flavor and sugar development to accommodate global shipping and storage. A 2-week postharvest storage with limited cluster or berry damage and minimal rachis dehydration may more than meet the standards necessary for local markets. Although large-scale production for schools or stores may require the need for cooling and storage, small-scale growers for farmers markets and consumer-supported agriculture subscriptions could be achieved without those resources. New cold-hardy cultivars being developed at the UMN would meet these local demands.

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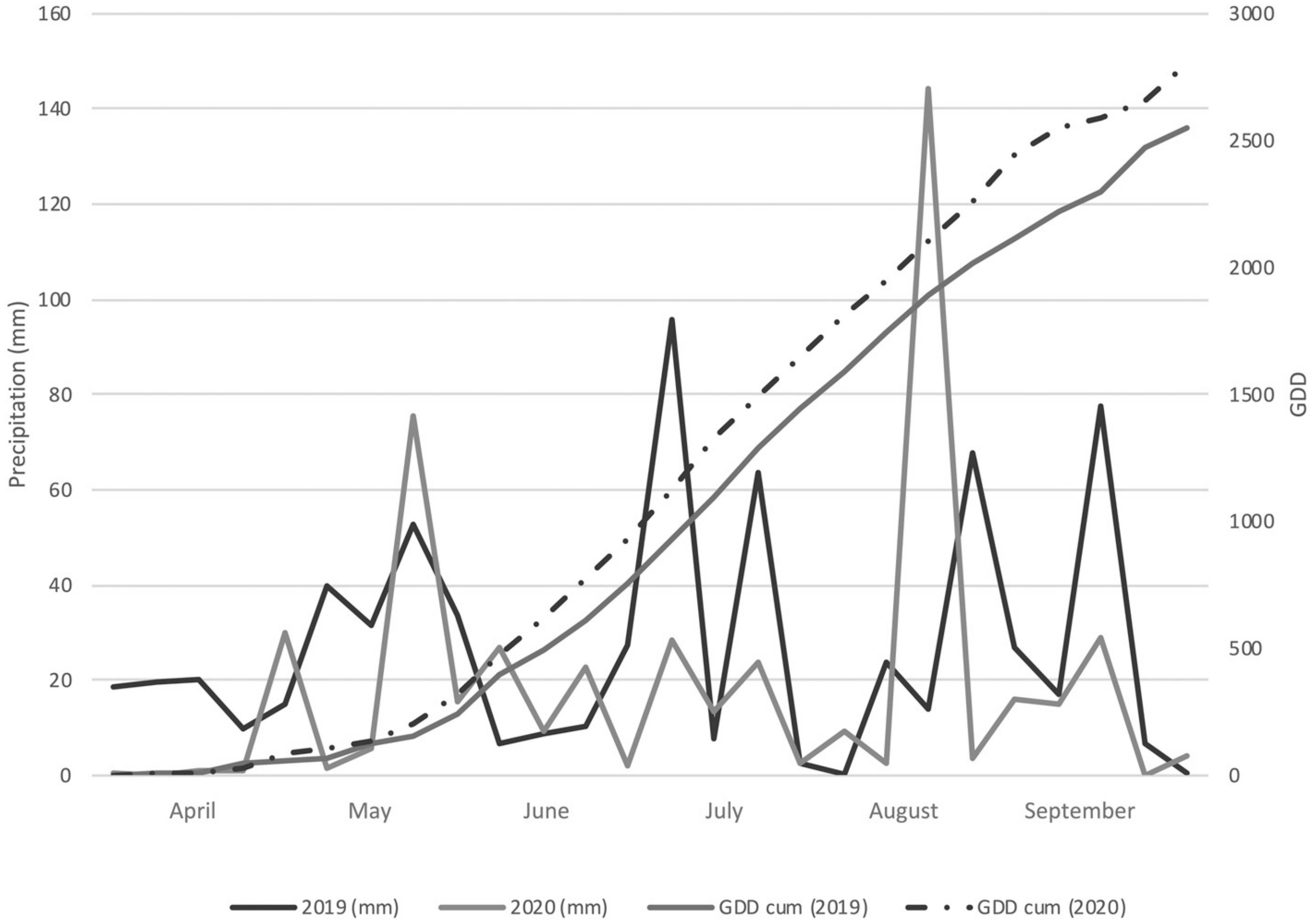
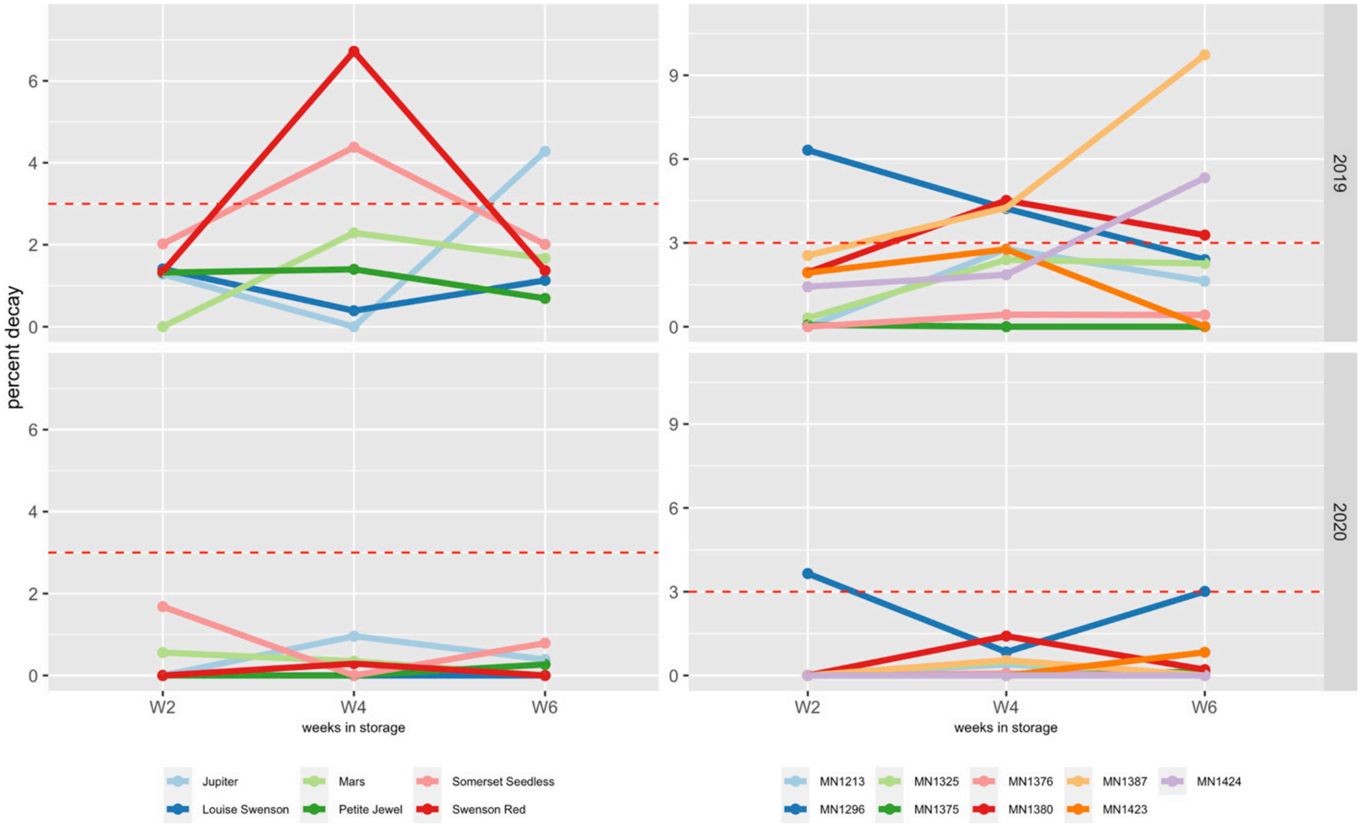
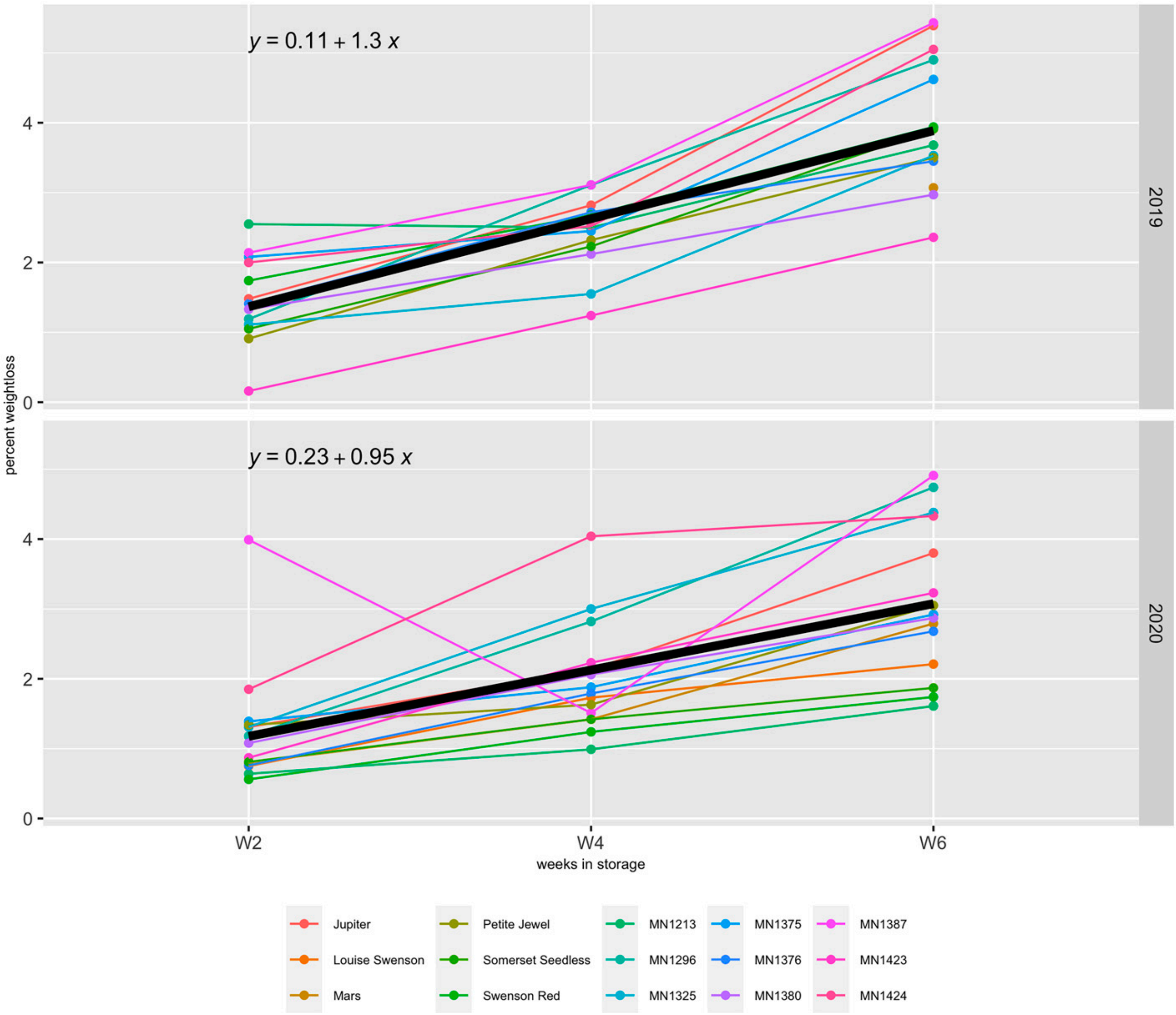


Supplemental Fig. S1. Weekly precipitation totals (mm) and cumulative growing degree days (GDD) for grape vines grown at the University of Minnesota (UMN) Horticultural Research Center (HRC), Excelsior, MN, for two growing seasons. Red asterisks denote the hail event in 2020. Clusters were harvested between 10–19 Sept. 2019 and 18 Aug. to 11 Sept. in 2020. Table 1 has dates for each cultivar.



Supplemental Fig. S2. Percent shatter for cold-hardy cultivars and advanced breeding selections (MN####) after cold storage (2.2 °C) for 2, 4, and 6 weeks. The red dashed line denotes the threshold of consumer acceptance for percent shatter. Each point represents one measurement of shattering per week per cultivar.



Supplemental Fig. S3. Percent weight loss for cold-hardy cultivars and advanced breeding selections (MN####) after cold storage (2.2 °C) for 2, 4, and 6 weeks. The red dashed line denotes the threshold of consumer acceptance for weight loss. Each point represents one measurement of weight loss per week per cultivar. The black line and equation indicate the linear trend line for each year.

Supplemental Table S1. Juice chemistry data at harvest for cold-hardy grape cultivars and advanced breeding selections grown in Minnesota. The total soluble solids (TSS) value is an average of three clusters with the juice of five berries per cluster. Data of postharvest storage of 2, 4, and 6 weeks. University of Minnesota (UMN) advanced breeding selections are indicated as MN####.

		TSS (°Brix)	
	Factors	2019	2020
	Treatment	—	—
	Genotype	***	***
	T × G	***	—
Treatment	Harvest	18.9 b	20.9 a
	2 weeks	19.3 ab	20.7 a
	4 weeks	19.2 ab	20.7 a
	6 weeks	19.2 b	21.3 a
Var.	Jupiter	18.9 c	21.1 def
	Louise Swenson	15.8 e	17.5 g
	Mars	16.3 de	17.1 g
	Petite Jewel	21.7 b	21.1 cdef
	Somerset Seedless	18.8 c	20.3 f
	Swenson Red	18.7 c	20.4 f
Adv. Sel.	MN1213	20.8 b	20.2 f
	MN1296	20.5 b	21.6 cdef
	MN1325	24.3 a	24.8 a
	MN1373	18.7 c	22.4 bcde
	MN1375	18.7 c	20.6 ef
	MN1376	18.4 c	17.8 g
	MN1380	20.7 b	20.5 f
	MN1387	20.7 b	20.6 ef
	MN1423	17.2 d	23.8 ab
	MN1424	19.0 c	20.6 ef

*Significance codes of the analysis of variance (ANOVA) results: *** = 0.001; ** = 0.01; * = 0.05. Post hoc groups were determined by Tukey's honestly significant difference test.